NPAL Data Analysis

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ATOC/NPAL Propagation Modeling

A scientific mystery has emerged from the analysis of bottom-mounted SOSUS hydrophone recordings of the broadband ATOC/NPAL source located just north of Kauai. Strong, robust arrivals are observed from several hundred meters below the turning point of predicted rays. This issue has been looked at extensively by Dr. Brian Dushaw of the UW-APL and Dr. John Colosi of the Woods Hole Oceanographic Institute. To date, the observations remain unexplained. Internal wave scattering is generally the first idea broached on the subject but work by Colosi and Heaney has shown that internal waves are not responsible for significant diffraction of a wavefront caustic in the vertical, particularly for high-angle rays. Here we will present the puzzle and show our explanation of the measurements based upon broadband parabolic equation and normal mode modeling as well as ray based modeling techniques. The ATOC and NPAL programs have been pioneers in examining the feasibility of global climate monitoring using long range acoustics. One of the decisions made during the early stages of this study was to place sources near shore where the local bathymetry interacts with the sound channel. This was done to eliminate the problem of source motion of a moored source in deep water and to facilitate the delivery of power to the source via underwater cables to land. This study examines the complex interaction of the sound with the local bathymetry before entering the deep ocean. The implications to the climate-monitoring field are significant.

Figure 1 shows an acoustic ray prediction of the arrival structure at the site, as well as the recorded data. The nominal depth of the receiver is overlaid on the prediction. It is clear that there are strong acoustic arrivals (SNR>30dB) arriving at a time corresponding to predicted rays that turn up to 800m shallower than the depth of the recorder. This observation was made at two separate hydrophone stations (path o and path n) separated by 500 km and is clearly evident in both data sets.

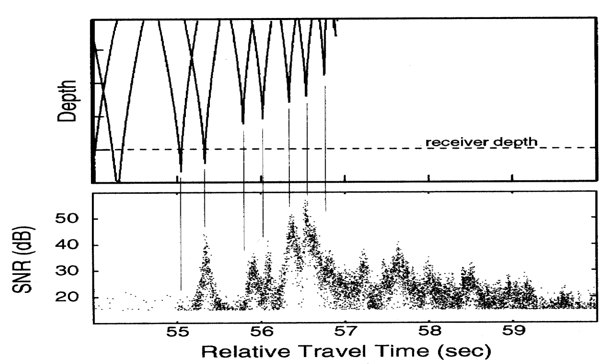

Figure 1. ATOC recording at receiver N (bottom-mounted SOSUS array) and ray based prediction of arrival structure. Figure taken from Dushaw et. al. IEEE-Journal of Ocean Engineering, 1999.

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Several questions arise from a careful look at the above picture. Firstly, how is sound scattered several hundred meters below turning point caustics of the wavefronts? The second question involves the early arriving wavefronts. The prediction indicates that early wavefronts (T~54 s) should be clearly visible at the receiver yet almost no indication of a corresponding wavefront is visible. A third issue is the arrival of energy 2 to 3 seconds beyond the strong arrivals and apparently beyond the axial cutoff.

To begin to look at this problem, the ray model used for the acoustic prediction must be examined. It is a standard ray-theory integration model developed by Scripps and has been well benchmarked against long-range broadband acoustic tomography experiments. To handle the interaction with the near-source bathymetry, it was observed that upward going rays at the source refract from the surface and enter deep water before interacting with the bottom. Higher angle rays and downward going rays (the source is several meters off the bottom) interact with the bottom several times and are expected to have significantly less energy then the purely waterborne rays. With these assumptions, a deep-water (bathymetry-less) environment was used and only the upward traveling rays at the source are retained. (Although in the figure above both rays are plotted.)

We examine the assumptions that upward going rays feel no influence of the bottom and that downgoing rays are effectively stripped from the water column from bottom interaction. To look into this problem broadband (30Hz BW centered at 75Hz) range-dependent PE runs were performed, as well as deep-water normal mode and ray solutions. The exact location of the receiver is classified and for purposes of illustrating the physics only an approximate path (taken from the IEEE paper) as well as an approximate sound speed profile was used. The features investigated are robust and therefore shouldn't depend on the exact bathymetry for examination.

The bathymetry used for the two paths studied is shown in figure 2. It is clear that over 95% of the propagation region is in deep water. For both profiles the bathymetry drops very quickly to 3000m but takes approximately 100km before reaching the abyssal plain depth of 5000 km. Path o encounters a seamount at a range of 150km. Seamounts are very common in the North Pacific, though the interaction of the sound with this particular seamount is beyond the scope of this work. The vertical extent of the seamount is to a depth of 3000 m so much of the sound energy will not be scattered.

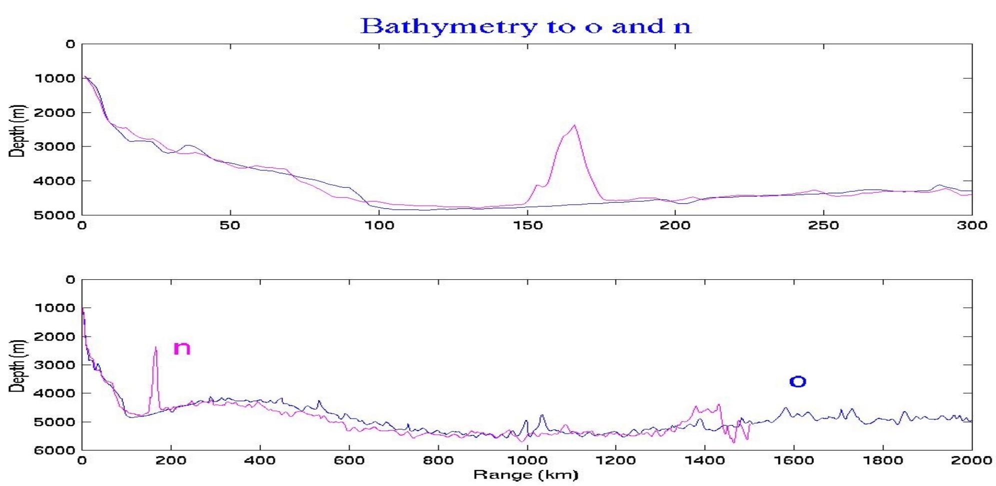

Figure 2. Bathymetry plotted vs. range for Kauai source to bottom-mounted hydrophones n and o.

Three models will be used to study the effects of the bathymetric scattering on the received broadband signal in the time-domain. A ray model will be used to calibrate our results with the ATOC group ray results as well as to decipher the number of bottom bounces each particular ray path has undergone before making it to the receiver. A broadband normal mode model using a range-independent profile and deep ocean will be used to look at time spreads and the energetics of the wavefronts for the predicted model. To examine time as well as energy for the bathymetric interacting case, a broadband PE model has been used.

The first set of results are for the normal mode and PE models run to a range of 100km down the slope. The question to be answered here is what is the structure of the sound that the source is putting into the deep water. The propagation for several thousand kilometers beyond this point is in deep water and we understand the issues corresponding to deep water propagation (travel time spread, internal wave scattering etc.)

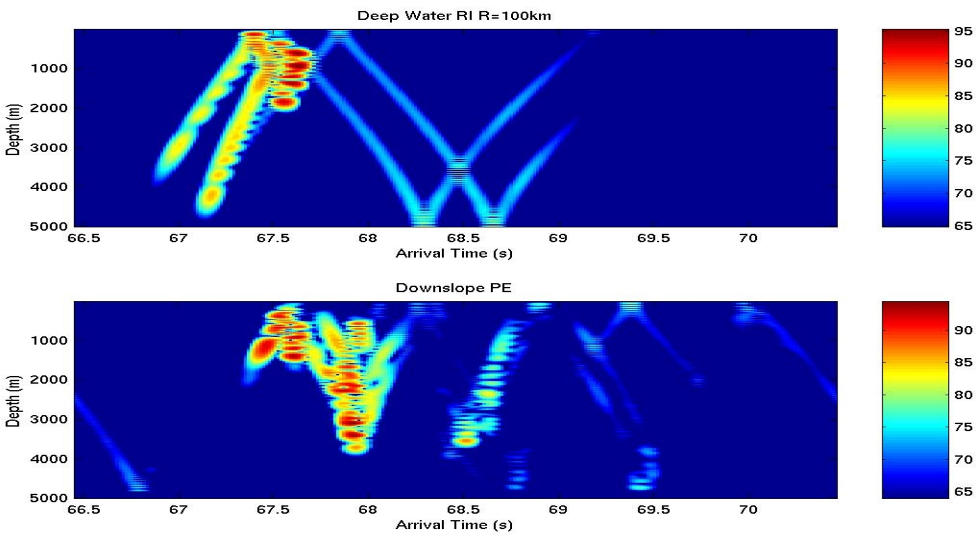

Figure 3. Broadband arrival time structures at a range of 100 km for deep-water normal mode and downslope PE calculations.

The results in figure 3 are staggering and the explanation of the physics of this pattern will be the subject of the remainder of this report. First looking at the top panel, the low-angle energy corresponding to the low mode numbers is clearly visible as the dominant axial arrival. This is the classic deep-water SOFAR crescendo. The early arriving wave doublet is high-angle energy that has a faster group velocity due to its penetration of the deep ocean where the sound speeds are significantly faster. The doublet feature is due to the upward and downward initial launch angles of the rays. The relatively faint, late arriving wavefronts correspond to even higher angle energy that is interacting with the bottom. This energy loses between 5 and 10 dB per bottom bounce and will not be observed at ranges beyond 1000 km. It does illustrate the behavior of high-angle sound having a very slow (relative to mode 1) group velocity when it interacts with the bottom. This is a common phenomenon in shallow water, where all the sound is bottom interacting and mode 1 is the fastest traveling mode.

Looking at the downslope PE result we see that the group velocity features are similar but the energetics are significantly different. The structure of the low-mode arrival is very similar to the deep-water result, indicating that the low angle energy has left the source region without interacting with the

bottom. The high-angle energy corresponding to the earliest wavefront arrivals exhibits two features. First, the downgoing energy (corresponding to the earliest wavefront in the deep water case) is completely stripped from the water. The upward going energy is stronger (>5dB) and has a significantly smaller time/depth spread at a range of 100km. This lack of time/depth spread will be significant to the overall time-spread of the signal at ranges of 1500km and beyond. The late arriving energy, corresponding to bottom interacting acoustic energy is significantly different in the presence of the bathymetry. The low level scattered energy that is arriving several seconds after the dominant arrivals will continue to interact with the bottom in the deep ocean and is therefore insignificant. The wavefront that arrives 0.3 s behind the axial arrival is significant because we will show that it no longer interacts with the bottom so will effectively propagate to distances of several thousand km. Several features of this wavefront are important. This wavefront has an equivalent amount of energy to the axial arrival. The time-delay has already been mentioned. The coherence of the wavefront indicates a robust feature.

Using a raytrace model the late arriving energies where associated with paths that bounce once or twice with the bottom. These rays will not encounter the bottom beyond 100km so they will have considerable energy when they arrive at the receivers. To compare with the data, we propagate the above signals to a range of 1500km. The results are shown in figure 4 for the deep-water range-independent normal mode solution and the downslope PE solution.

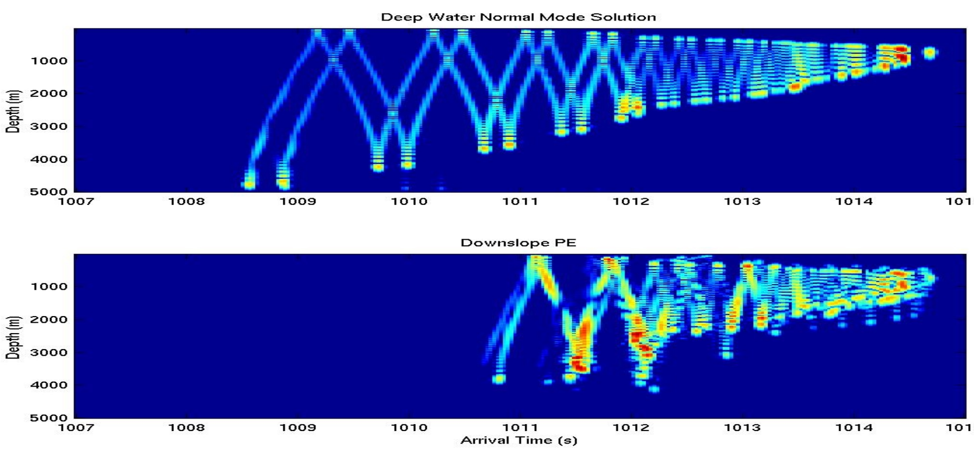

Figure 4. Broadband receptions at a range of 1500km for the deep water normal mode solution and the downslope Parabolic Equation solution.

The effect of the bathymetric scattering on the time-spread of the wavefronts is evident at this range. The energy corresponding to the axial cut-off has the same travel time indicating its insensitivity to the bathymetry near the source. For the downslope case, faint high angle energy is visible in the axial cutoff and these correspond to remnants of the bottom bounce near the source. It was shown in Dr. Heaney's previous ONR contract that these faint echos, coupled with internal waves are responsible for the nearly 1 second afterglow observed in the ATOC data. Two significant differences remain between the calculation. The first is the 2.5 s smaller time spread from last to earliest arrival of the downslope case. This was visible in the 100km result as the time spread of the highest angle energy was clipped by bottom scattering. This difference will have significant implications to the ray-ID problem of the tomography community. Internal waves scatter the axial arriving energy so strongly that determining the time of the axial cutoff is impossible with long range data. Without the benefit of knowing the cutoff time, ray-ID's are determined by overlaying data with predictions. If the early

arriving wavefronts are not present and they are assumed to be present, then a mismatch of ray-ID is possible.

The other feature evident in the comparison of the two simulations is the intensification and deepening of the earliest arriving wavefronts for the downslope PE case. The results at 100km explain the increase in energy observed as a strong single (or double) bounce from the bottom. The existence of sound several hundred meters below the turning point of the corresponding deep-water simulation wavefronts is explained as a travel time delay due to bottom interaction. The travel time delay at 100km was approximately 1 full second, which corresponds (at 1500km) to the time difference between arriving wavefronts.

As a final step, we compare the line plot of the received signal for a hydrophone averaged over 3500-3750m in depth. The average is taken to smooth out the high-frequency wavefront effects, which we do not expect to be able to model without exact environmental and receiver position information.

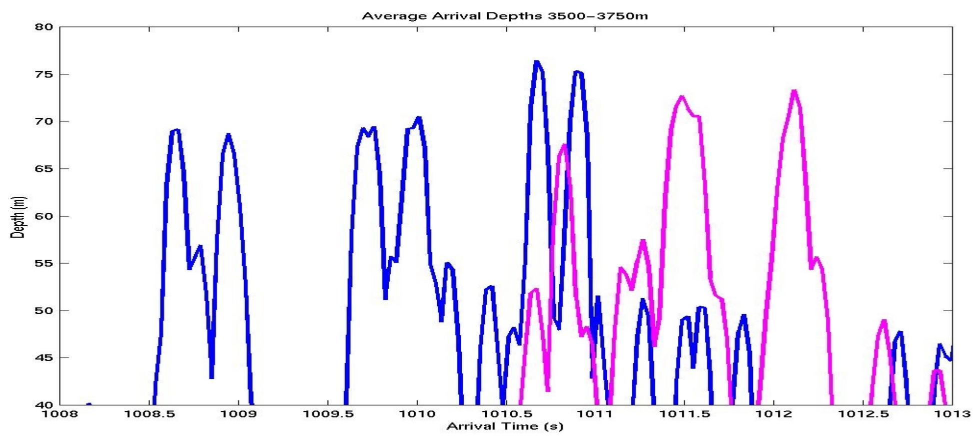

Figure 5. Average reception (depths=3500-3750m) for deep-water (blue) and downslope PE (maroon) calculations.

The deep-water (blue) simulation shows the early arrivals corresponding to the high-angle energy and then quickly fades as the rays turn above the receiver. The evidence of 25 dB stronger arrivals at times of 1011.5 and 1012 s we believe explains the anomaly observed in the data. The increasing energy for each bounce also agrees qualitatively with the data. In addition to the presence of late arriving energy, the lack of early arriving energy is apparent in our results.

We believe that we have explained the anomalous presence of stable, strong acoustic arrivals at a receiver whose depth is several hundred meters below the turning point of ray predictions. This effect is not a scattering of energy in depth, as was previously assumed. In contrast to scattering in depth, the effect is a time delay due to the relatively slow group velocities of the high-angle energy in the presence of bathymetry. The interaction with the bathymetry very near the source also explains the lack of early arriving wavefronts visible in the data. The implications of this work to climate modeling using long-range acoustic transmissions from bottom mounted sources is significant and will be examined as an extension of this work.

III. ATOC Spectrogram Analysis

In addition to the NPAL/ATOC broadband simulation study just presented, this quarter Dr. Heaney worked with Dr.'s Kuperman and D'Spain at the Scripps Institution of Oceanography finishing up work on the structure of single phone spectrograms for long-range acoustic propagation. It was shown that for certain sound speed profiles, the spectrogram of a single hydrophone could reveal the source range with a precision of 100km at a range of 3500km. The results of this finding have been submitted to the Journal of the Acoustical Society of America and were presented at the recent meeting of the ASA in Columbus.